Renewable and Sustainable Energy Reviews 15 (2011) 131–149

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review

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ARTICLE INFO

Article history:
Received 21 July 2010
Accepted 6 August 2010

Keywords:
Inedible vegetable oils
Alternative fuel
Biodiesel
CI engine
Performance and emission characteristics

ABSTRACT

The use of inedible vegetable oils as an alternative fuel for diesel engine is accelerated by the energy crisis due to depletion of resources and increased environmental problems including the great need for edible oil as food and the reduction of biodiesel production cost, etc. Of a lot of inedible vegetable oils which can be exploited for substitute fuel as diesel fuel, seven vegetable oils, i.e., jatropha, karanja, mahua, linseed, rubber seed, cottonseed and neem oils were selected for discussion in this review paper. The application of jatropha oil as a liquid fuel for CI engine can be classified with neat jatropha oil, engine modifications such as preheating, and dual fuelling, and fuel modifications such as jatropha oil blends with other fuels, mostly with diesel fuel, biodiesel, biodiesel blends and degumming. Therefore, jatropha oil is a leading candidate for the commercialization of non-edible vegetable oils. There exists a big difference in the fuel properties of seven inedible vegetable oils and its biodiesels considered in this review. It is clear from this review that biodiesel generally causes an increase in NOx emission and a decrease in HC, CO and PM emissions compared to diesel. It was reported that a diesel engine without any modification would run successfully on a blend of 20% vegetable oil and 80% diesel fuel without damage to engine parts. This trend can be applied to the biodiesel blends even though particular biodiesel shows 40% blend. In addition, the blends of biodiesel and diesel can replace the diesel fuel up to 10% by volume for running common rail direct injection system without any durability problems.

Contents

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doi:10.1016/j.rser.2010.08.012

1. Introduction

It is known that the remaining global oil resources appear to be sufficient to meet demand up to 2030 as projected in the 2006–2007 world energy outlook by the IEA [1]. There is, therefore, a demand to develop alternative fuels motivated by the reduction of the dependency on fossil fuel due to the limited resources. Several oxygenated fuels are known to have the potential for use as the alternative gasoline and diesel fuel. Those oxygenates can be classified as alcohol, ether, ester, carbonate and acetate compounds. Alcohol compounds include ethanol, methanol, propanol, butanol etc. Of ether compounds, DME (di-methyl ether) is one of the leading candidate of alternative diesel fuel [2,3]. The biodiesel which is one of substitute for diesel fuel belongs to ester compound in the above classification. The term "biodiesel' commonly refers to an oxygenated diesel fuel made from various feedstock by conversion of the triglyceride fats to methyl or ethyl esters via transesterification. In general, biodiesel feedstock can be categorized into four groups [4]: oilseeds (edible or inedible oil), animal fats, waste materials and algae as shown in Table 1. In this table, vegetable oils can be obtained from oilseeds and it can be divided into edible and non-edible oils. In addition, it is subdivided into conventional or traditional and alternative feedstocks. It should be noted that even though rice bran oil can be belong to inedible oil in some country such as India, it is included in edible oil in Korea. However, Balat and Balat [14] classified oilseeds and algae as vegetable oils and categorized the biodiesel feedstock into three groups: vegetable oils (edible or inedible oil), animal fat and used waste cooking oil. Other two important types of alternative diesel fuel as well as DME and biodiesel include Fischer-Tropsch diesel (coal-to-liquid CTL, gas-to-liquid GTL, and biomass-to-liquid BTL) and neat vegetable oil [51,52]. Pure or raw plant oil [53], straight vegetable oil [54], pure vegetable oil [55], and virgin vegetable oil [56] are used as synonym with neat vegetable oil. In addition to four alternative diesel such as DME, F-T diesel, biodiesel and neat vegetable oil, renewable diesel can be added to alternatives to petroleum-based diesel fuel (petrodiesel). Renewable diesel, hydrotreated vegetable oil (HVO) or green diesel is produced from the lipid feedstocks such as the fat or oil by a hydrodeoxygenation reaction at elevated temperature and pressure in the presence of a catalyst [57,58].

The different types of edible vegetable oils and biodiesels as substitutes for diesel fuels are considered in the different countries depending on the climate and soil conditions. For example, soybean oil in the USA, rapeseed (canola in Canada) and sunflower oils in Europe, palm oil in South-east Asia (mainly Malaysia, Indonesia and Thailand), coconut oil in the Philippines and cottonseed oil in Greece and Turkey are being produced [59]. Canola is the name generally applied to rapeseed that has low amounts of erucic acid in its oil and low levels of glucosinolates in its meal [60].

Even though biodiesel production from edible vegetable oil has many advantages for combustion in CI engines, important disadvantages of biodiesel include high feedstock cost, inferior storage and oxidative stability, lower heating value, inferior low-temperature operability and higher NOx emissions compared to petrodiesel [4]. The problem of high feedstock cost can be mitigated by the selection of inedible vegetable oil for the production of biodiesel because the cost of feedstocks accounts about 60–80% of the total cost of biodiesel production [61,62]. It is clear from the recent review [63] for the perspectives on biodiesel as a sustainable fuel that using low cost feedstocks is one of the key

Table 1
Feedstocks categories of biodiesel production.

Category	Classification		Feedstocks	References
1. Oilseeds	edible	C:	Soybean, rapeseed/canola, sunflower, palm, coconut, olive	[5–7]
		A:	False fax, safflower, sesame, marula, pumpkin, African peer seed, *Sclerocarya birrea*, *Terminalia catappa* L., yellow nut-sedge tuber, rice bran	[4,6,8–13]
	inedible	A:	Jatropha, karanja, mahua, linseed, ruberseed, cottonseed, neem, camelina, putranjiva, tobacco, polanga, cardoon, deccan hemp, castor, jojoba, moringa, poon, koroch seed, desert date, eruca sativa gars, see mango, pilu, crambe, syringa, milkweed, field pennycress, stillingia, radish Ethiopian mustard, tomato seed, kusum, cuphea, camellia, paradise, cuphea, treminalia, *michelia champaca, garcinia indica, zanthoxylum bungeanum*	[6,14–42]
2. animal fats		C:	Beef tallow, pork lard	[43]
		A:	Waste salmon, melon bug, sorghum bug, chicken fat	[4]
3. waste materials		C:	Cooking oil, frying oil	[44,45]
		A:	Vegetable oil soapstocks, acid oils, tall oil, dried distiller's grains (DDG), pomace oil	[4,46,47]
4. algae			*Botryococcus braunii, Chlorella* sp., *Chrolella vulgaris, Crypthecodinium chonii, Cylindrotheca* sp., *Dunaliella primolecta, Dunaliella salina, Isochrysis* sp., *Haematococcus pluvialis, Monallanthus salina, Muriellopsis* sp. *Nannochloris* sp., *Neochloris oleoabundans, Nitzschia* sp., *Phaeodactylum tricornutum, Porphyridium cruentum Schizochytrium sp., Spirulina, Arthrospira platensis, Tetraselmis sueica*	[48–50]

C: conventional; A: alternative.

issues including improving efficiency of the production process, developing cost effectives catalyst and managing agricultural land. Development of low-value alternative feedstocks for biodiesel production is, therefore, one of important field of current and future research. The use of edible vegetable oil or biodiesel from it as substitutes to diesel fuels may lead to a problem of self-sufficiency in vegetable production. The use of non-edible vegetable oils is of significance because of the great need for edible oil as food. In addition the selection of non-edible vegetable oil can reduce the production cost of biodiesel due to the relatively high cost of edible vegetable oils. In this review, therefore, only the inedible vegetable oils and biodiesel produced from them for alternative diesel fuel in compression ignition (CI) engines will be focused.

The review about the combustion of fat and vegetable oil derived fuels in CI engines was published by Graboski and McCormick in 1998 [64]. In this review, edible vegetable oils were mainly included. They emphasized that the major obstacle to widespread use of biodiesel is the high cost (mainly due to high price of edible vegetable oils) relative to petroleum diesel even though biodiesels can be suitable fuels for CI engines. They also found that emissions of particulate matter can be reduced remarkably through use of biodiesel in engine, but NOx emissions increase dramatically for both neat and blended fuels in both two- and four-stroke diesel engines.

A precise review of research on biodiesel fuel sources, properties, exhaust emissions by using biodiesel fuel etc were reported by Kann et al. [65]. They summarized that the biodiesel from edible vegetable oils produced less CO, HC and PM compared to petrodiesel. Particulate emission reduction can be attributed to oxygen content in esters and lack of aromatic compounds. However, NOx emissions are higher for biodiesel than for petrodiesel, but not always.

Babu and Devaradjane [66] reported the review work on the performance and emission characteristics of neat vegetable oil, biodiesel, and its blends in CI engine. Their results show that compared to No. 2 diesel fuel, all of the vegetable oils are much more viscous, are much more reactive to oxygen, and has higher cloud point and pour point. They also found that compared with diesel fuel, vegetable oils and their biodiesels offer lower engine noise, and lower smoke, HC, and CO, slightly higher NOx and higher thermal efficiency. In addition, 25/75 blend of vegetable oil with diesel fuel, 20/80 blend of biodiesel with diesel fuel offers better engine performance and lower emissions. However, they had concentrated mainly on the study of the performance and emission characteristics for edible vegetable oils and its derivatives.

Agarwal [67] reported the review on the biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. This work reviewed the production, characterization and current statues of vegetable oil and biodiesel as well as the experimental research works. It should be noted that this paper summarized the engine tribology investigations of biodiesel and economical feasibility of biodiesel. In addition, it is found in this work that diesel engine can perform satisfactory for long run on biodiesel without any hardware modification and twenty percent biodiesel is the optimum concentration for biodiesel blend with improved performance.

Recently, the works about diesel engine emissions when using biodiesel fuels as opposed to conventional diesel fuels were reviewed and compared by Lapuerta et al. [68], paying special attention to the most concerning emissions: nitric oxide and particulate matter. The effect of biodiesel fuel on brake effective power, specific fuel consumption and thermal efficiency was included as the basis for comparison. They concluded that the highest consensus were in the sharp reduction in particulate emission and in an increase in fuel consumption in approximate proportion to the loss of heating value, when using biodiesel fuels as opposed to conventional diesel fuels. In addition, they found that most of studies reported the slight increases in NOx emissions when using biodiesel fuels.

A literature review of use of biodiesel fuel for CI engines between 1900 and 2005 was reported recently by Shahid and Jamal [69]. In this article, the typical edible vegetable oils such as sunflower, cottonseed, rapeseed, soybean, palm and peanut oils were included. They recommended the rapeseed oil and palm oil as the most suitable oils which can be used as diesel fuel extender. They concluded in this work that neat vegetable oils can be used only for small engines for a short-term period. For long-term use and for heavy/big engines, blend of diesel and vegetable oils was recommended. Moreover, the biodiesel produced much less NOx and HC and absolutely no Sox and no increase in CO_2 at global level. In addition, they found that indirect fuel injection system is more successful as compared to direct injection system while using vegetable oils in place of diesel oil. However, it should be noted that their conclusion came from the review of the limited number of edible vegetable oils.

According to the review on progress and recent trends in biodiesel fuels [5], blends of up to 20% biodiesel mixed with petroleum diesel fuels can be used in nearly all diesel equipment and are compatible with most storage and distribution equipment. Neat biodiesel and biodiesel blends reduced PM, HC and CO emissions and slightly increased NOx emissions compared with petroleum-based diesel fuel used in an unmodified diesel engine.

A comprehensive review of using both edible and inedible vegetable oils in CI engines had been carried out by Hossain and Davis [53]. Even though they included some inedible vegetable oils in their review, there was no consistency of data for them in Tables and Figures. However, it should be noted that life-cycle analysis and greenhouse gas emission analysis were included. They concluded that the life-cycle output-to-input energy ratio of raw vegetable oil is around 6 times higher than fossil diesel and is in the range of 2–6 times higher than corresponding biodiesel. In addition, neat vegetable oil has the highest potential of reducing life-cycle greenhouse gas emissions as compared to biodiesel and fossil diesel.

It is clear from the existing reviews discussed in the above that review pertained to inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines could not be found. In this paper, an attempt has been made to review the work done on the application of inedible vegetable oils and their derivatives as substitute fuel to CI engines. The main objective of this study is to introduce the appropriate inedible vegetable oils and its derivatives to run CI engine efficiently and economically as alternative diesel fuels.

2. Selection of inedible vegetable oils for possible alternative diesel fuel

The advantages of non-edible vegetable oil as a diesel fuel are liquid nature portability, ready availability, renewability, higher heat content, lower sulphur content, lower aromatic content, and biodegradability. On the other hand, the disadvantage of non-edible vegetable oil as a diesel fuel are higher viscosity, lower volatility, the reactivity of unsaturated hydrocarbon chains, and higher percentage of carbon residue [70].

For the selection of inedible vegetable oils for possible alternative diesel fuel, it is required to review the existing review works. The development up to 2003 on the use of vegetable oils and its blends, biodiesel and its blends in CI engines were reviewed by Babu and Devaradjane [66]. They selected eight non-edible vegetable oils such as neem, karanja, mahua, jatropha, polanga (hone, nagchampa), castor, linseed and crambe oils, and 11 edible

vegetable oils such as sunflower, soybean, sesame, safflower, coconut, cottonseed, olive, palm, peanut, corn and rapeseed oils for a survey of studies and research on vegetable oil based fuels.

Fatty acid profiles of seed oils of 75 plant species having 30% or more fixed oil in their seed/kernel were examined by Azam et al. [35]. Out of these plants, 26 species including jatropha, karanja, neem, and polanga seed oils were found to be most suitable for use as biodiesel because they met the biodiesel standards of USA, Germany and European Standard Organization.

In the review of production, characterization of vegetable oils and their methyl ester as the substitute of the petroleum fuel [67], four inedible oils such as jatropha, karanka, polanga and rubber seed oils were recommended as the main sources for biodiesel production.

As one of the low cost feedstocks and the inedible vegetable oils for reducing the dependency on edible oil to make biodiesel, Gui et al. [62] recommeded jatropha, karanja, castor, rubber seed and see mango. For making biodiesel a sustainable resource replacing fossil diesel fuel without significantly affecting the global food economy, they concluded that as the low cost feedstocks, waste edible oil should be made the primary source for biodiesel feedstock and non-edible vegetable oils can be used to supplement the shortfall of waste edible oils as feedstocks.

Advancements in development and characterization of biodiesel, mainly concentrating the effect of the different parameters on production of biodiesel such as molar ratio, moisture and water content, reaction temperature, stirring, specific gravity, etc. was reviewed by Sharma et al. [71]. They recommended that developing countries are not self sufficient in the production of edible oils and hence have emphasized in the application of a number of non-edible oils such as jatropha, karanja, mahua, rubber seed, neem and polanga etc. However, the inedible oils with high value of oil content such as polanga seed oil have not caught the attention of researchers and biodiesel manufacturers.

Achten et al. [72] recently reviewed the currently available information on the different process steps of the production process of biodiesel from jatropha oil, being cultivation and production of seeds, extraction of the oil, conversion to and the use of the biodiesel and the by-products. However, the use of jatropha oil in CI engine in this review was based on the limited number of papers in the literature.

A review on the performance and emission characteristics of five inedible vegetable oils, i.e. karanja, mahua, linseed, rubber seed, and cottonseed oils, as a substitute for diesel fuel was reported [73]. However, jatropha oil, one of typical non-edible vegetable oils, was not included in this review. In his continued work [74], fuel properties of jatropha oil and its biodiesel, fuel modification such as blending with other fuels, biodiesel, biodiesel blends, and degumming, engine modification such as dual fuelling and reheating were extensively examined.

Recently, Demirbas [5] reported the progress and recent trends in biodiesel fuels. He concluded that the edible oils in use at that time were soybean, sunflower, rapeseed and palm and the inedible oil used as feedstock for biodiesel production includes jatropha, karanja, mahua, polanga, neem, rubber seed, silk cotton tree, waste cooking oil and microalgae, etc. The main advantages of biodiesel include its domestic origin, its potential for reducing a given economy's dependency on imported petroleum, biodegradability, high flash point, and inherent lubricity in the neat form. The main disadvantages of biodiesel are its higher viscosity, lower energy content, higher cloud point and pour point, lower engine speed and power, injector coking, engine compatibility, and high price. Blends of up to 20% biodiesel mixed with petroleum diesel fuels can be used in nearly all diesel equipment and are compatible with most storage and distribution equipment. Neat biodiesel and biodiesel blends reduce PM, HC and CO emissions and slightly increase NOx emissions compared with petroleum-based diesel fuel used in an unmodified diesel engine. This paper was directly included in the text book for post-graduates in energy-related studies, fuel engineers and scientists, etc. [75].

As the inedible and low-cost vegetable oils with high potential to be used as raw materials to produce biodiesel, Pinzi et al. [76] selected thirteen vegetable oils and analyzed in terms of fuel properties and their suitability to be used as alternative diesel fuel. They found that biodiesels from jatropha, karanja, mahua, neem and castanhola oils among the studies inedible vegetable oils selected for evaluation fitted current biodiesel standards, i.e. European EN 14214 and US ASTM D 6751-02. In addition, they concluded that jatropha and karanja oils are more suitable to be used under cold climates when compared to the others.

Recently, a comprehensive review by Moser [4] covered the advantage and disadvantage of biodiesel, the process by which biodiesel is prepared, the effect of FFA on biodiesel production, the effect of biodiesel composition on fuel properties, etc. A particular emphasis was placed on alternative feedstocks from oilseeds, animal fats and waste oils for biodiesel production. Out of oilseeds, five edible (false fax, safflower, sesame, marula and pumpkin) and nineteen inedible oils were recommended. Nineteen inedible vegetable oils as alternative feedstocks for biodiesel production included jatropha, karanja, mahua, syringe, moringa, tobacco seed, desert date, castanhola, rubber seed, tung, milkweed, rice bran, radish, eithopia mustard, polanga, cardoon, jojoba, *Zanthoxylum bungeanum*. In addition, future challenges and outlook for biodiesel were discussed.

In a critical review of biodiesel as a vehicular fuel, Balat and Balat [77] found that there are more than 350 oilseed crops identified, among which only edible oils such as sunflower, safflower, soybean, rapeseed and peanut oils are considered as potential alternative fuels for diesel engines. For the non-edible vegetable oils as biodiesel feedstock, Balat and Balat [14] recommended jatropha, karanja, tobacco seed, rice bran, mahua, need and rubber seed oils in their continued work. Only jatropha, karanja and mahua oils were, however, briefly explained in their review on progress in biodiesel processing.

Recently in the review of the source of production and characterization of vegetable oils and their methyl ester as the substitute of the petroleum fuel [6], the performance of vegetable oil and biodiesel as a fuel was included and four inedible oils such as jatropha, karanka, polanga and rubber seed oils suggested originally by Agarwal [67] were recommended as the main sources for biodiesel in India.

Based on the review works considered in this study, it can be found that there are a lot of trees, shrubs and herbs in the world which can be exploited for substitute fuel as diesel fuel. The raw materials being exploited commercially and scientifically by many researchers constitutes the non-edible oils derived from jatropha, karanja (pongamia, honge), mahua, linseed, rubber seed, cottonseed, neem, putranjiba, tobacco seed, polanga seed, cardoon, deccan hemp, castor, jojoba, moringa, cuphea, poon, koroch seed, desert date. balnites, eruca sativa gars, pilu, crambe, milkweed seed, radish, see mango, etc. [78].

Following a literature survey it has been decided to select the inedible oil as a possible fuel for use in a diesel engine. Various inedible vegetable oils, promising substitute for petroleum based diesel and acceptable feedstock for biodiesel production, are shown in Table 2. The oil content in the seed and kernel and free fatty acid content are also included. It is clear from Table 2 that the oil content in seed/kernel for several inedible vegetable oils is widely different according to the literature. The data were, therefore, summarized as the minimum and maximum as range for the oil content.

Camelina oil which is not included in Table 2 was classified as edible oil by Demirbas [5] and as inedible oil by Singh and Singh

Table 2
Various inedible vegetable oils with oil and free fatty acid contents.

Vegetable oil	Oil content		Free fatty acid (wt%)	References
	Seed (wt%)	Kernel (wt%)		
Jatropha (*Jatropha curcas*)	20–60	40–60	13.5–14.5	[4,6,35,71,79–84]
Karanja (*Pongamia pinnata*) =Honge	25–50	30–50	8.3– 20	[4,6,70,71,76,85–90]
Mahua (*Madhuca indica*)	35–50	50	20	[4,6,35,71,91]
Linseed (*Linum usitatissimum*)	35–45			[6,92]
Rubber (*Hevea brasiliensis*)	40–60	40–50	17	[5,93,94]
Cottonseed	17–25			[95]
Neem (*Azadirachta indica*)	20–30	25–45		[6,35]
Putranjiva (*Putranjiva roxburghii*)	42			[35,71]
Tobacco (*Nicotiana tabacum*)	36–41	17		[4,71]
Polanga (*Calophyllum inophyllum*)	65	22		[4,35,71]
Cardoon (*Cynara cardunculus*)	25–26			[4,38,96,97]
Deccan hemp (*Hibiscus cannabinus*)	13			[4,16]
Castor (*Ricinus communis*)	45–50			[4,6]
Jojoba (*Simmondsia chinensis*)	45–55			[6,98–100]
Moringa (*Moringa oleifera*)	33–41	2.9		[18,29,35]
Poon (*Sterculia foetida*)	50–55			[4,21]
Koroch seed (*Pongamia glabra*)	33.6			[4,23]
Desert date (*Balanites aegyptiaca*)	45–50			[4,26]
Eruca Sativa Gars	35			[27]
See mango (*Cerbera odollam*)	54	6.4		[4,19]
Pilu (*Salvadora oleoides*)	45			[35]
Crambe (*Crambe abyssinica*)	38			[36]
Syringa (*Melia azedarach*) = Persian lilac	10–45	2.8		[35]
Milkweed (*Asclepias syriaca*)	20–25	0.019		[4,28,76]
Field pennycress (*Thlaspi arvense* L.)	20–36			[31,101]
Stillingia (*Sapium sebifeum* Lin. *Roxb*)	13–32			[33]
Radish (*Raphanus sativus*)	40–54			[4]
Ethiopian mustard (*Brassica carinata*)	42	2.2–10.8		[25,76]
Tomato seed	32–37			[30]
Kusum (*Scheleichera triguga*)	10.65			[20]
Michelia chaampaca	45			[34]
Garcinia indica	45.5			[34]
Zanthoxylum bungeanum	24–28	25		[4,32]

[6], Pinzi et al. [76]. According to Zubr [102], *Camilina sativa* seed consists of about 43% oil in dry matter and the camilina oil was found to be applicable in salads, for cooking, baking and frying.

It is found from Table 2 that most inedible vegetable oils exhibit high level of free fatty acids (FFA). It is well known that transesterification for producing biodiesel was not feasible if free fatty acids (FFA) content in the oil was more than about 3.0%. For oil samples with FFA value below 2.0%, alkaline transesterification is preferred over the acid transesterification as the former is reported to proceed about 4000 times faster than the latter [71,103]. Therefore, most inedible vegetable oils in Table 2 require the two-step transesterifications for obtaining biodiesel [104]. The production cost of biodiesel between from edible vegetable oil and from inedible vegetable oils should be precisely analyzed.

In this article, the status of inedible vegetable oils and its derivatives with respect to fuel properties, application methods, engine performance and emissions will be reviewed and discussed. Out of many inedible vegetable oils which can be exploited for alternative fuel for diesel fuel and shown in Table 2, seven vegetable oils, i.e. jatropha, karanja, mahua, linseed, rubber seed, cottonseed and neem oils were selected for discussion. The selection of seven inedible vegetable oils are primarily based on three criteria such as oil content in the feedstock, available number of literature and recommendation of the previous review study. Out of seven inedible vegetable oils considered, linseed oil was classified as edible oil by Azam et al. [35]. However linseed oil was grouped as inedible oil source by Subramanian et al. [105], and Agarwal et al. [106]. In addition, cottonseed oil was classified as non-edible oil by Eevera et al. [107], Kansedo et al. [19], Subramanian et al. [105] and Subramanian et al. [80] and as edible oil by Alptekin and Canakci [108] and Rashid and Anward [8].

3. Fuel properties of seven inedible vegetable oils

The fuel properties of seven inedible vegetable oils are shown in Table 3. The data from the various literatures are summarized as the minimum and maximum values as range for the fuel properties. It is clear that the fuel properties of seven inedible vegetable oils are widely different according to climate, soil, variety, etc. Compared to diesel fuel, higher density and kinematic viscosity, lower cetane number and calorific value of vegetable oils are shown. Because of the low cetane number and high kinematic

Table 3
Fuel properties of seven inedible vegetable oils and diesel.

Property	Jatropha	Karanja	Mauha	Linseed	Rubber seed	Cottonseed	Neem	Diesel
Density (kg/m^3, 40 °C)	901–940	870–928	891–960	865–950	910–930	911–921	912–965	–
Viscosity (mm^2/s, 40 °C)	24.5–52.76	27.8–56	24.6–37.6	16.2–36.6	34.0–76.4	32.8–36.0	20.5–48.2	2.0–2.7
Flash point (°C)	180–280	198–263	212–260	108–242	144–198	210–243	34–285	45 min
Pour point (°C)	−3 to 5	−3 to 6	12–15	−15 to −4	−1	−10 to 16	–	−20 to 5
Cloud point (°C)	8–10	13–15	12	1.7–2.0	14	−8.7 to 1.7	–	–
Cetane number	33.7–51	45–67	43.5	28–35	37	41.2–59.5	51	45 min
Calorific value (MJ/kg)	38.20–42.15	34.0–38.8	35.6–38.9	37.7–39.8	37.5	39.5–40.1	33.7–39.5	–

Table 4
Fuel properties of seven biodiesels and American standards.

Property	JOME	KOME	MOME	LOME	ROME	COME	NOME	ASTM*
Density (kg/m^3, 40 °C)	862–886	865–898	828–865	874–920	858–900	872–885	820–942	870–900
Viscosity (mm^2/s, 40 °C)	3.0–5.65	3.8–9.6	2.7–6.2	3.36–8.91	1.9–6.0	3.6–5.94	3.2–10.7	1.9–6.0
Flash point (°C)	180–280	110–187	56–208	161–181	130–174	70–200	–	>130
Pour point (°C)	2–6	−6 to 14	1–6	−18 to 14	−15 to 10	−15 to 6.0	–	−15 to 10
Cloud point (°C)	4–10	−2 to 24	3–5	−3.5	−3 to 12	–	–	–
Cetane number	43–59	36–61	47–51	48–59	49–57	45–60	51–53	47 min
Calorific value (MJ/kg)	37.2–43.0	36.0–42.1	36.8–43.0	37.5–42.2	36.5–42.1	40..1–40.8	39.6–40.2	–

viscosity of the inedible vegetable oil, several problems in diesel engines such as engine choking, cease of fuel injector, gum formation and piston sticking under long term use may occur [109].

Table 4 shows the fuel properties of seven methyl esters obtained from inedible vegetable oils and American standards. The physical properties of biodiesel fuel depended upon the structure and type of the fatty acid esters present [94]. The properties of biodiesel also depend on the type of the vegetable oil used for the transesterification process [110]. Biodiesel is completely miscible with diesel and can be blended in any proportion to diesel fuel. It is found from Table 4 that most of fuel properties of several biodiesels are within the standards. It is, therefore, clear that some biodiesel, particularly jatropha oil methyl ester (JOME), can be applied directly to CI engines.

Because of the high molecular weights (about 880), vegetable oil have low volatility [80]. In any case, the viscosity of neat vegetable oil and neat biodiesels is higher than that of typical diesel fuel. High viscosity of vegetable oils and biodiesel leads to poor atomization of fuel spray, in turn large droplet size and thus high spray jet penetration. The jet tends to be a solid stream instead of a spray of small droplets. As a result, the fuel is not distributed or mixed with the air required for burning in the combustion chamber. This result of poor combustion will be accompanied by loss of power and economy.

Vegetable oils can be successfully applied in CI engine through fuel modifications and engine modifications. Fuel modifications include blending of vegetable oils with petrodiesel or other fuel, pyrolysis (thermal cracking), micro-emulsion [111], transesterification, and hydrodeoxygenation to reduce polymerization and viscosity. Preheating/ heated fuel line, dual fueling, and injection system modification, etc belong to engine modifications.

Heating and blending of vegetable oils reduce the viscosity but its molecular structure remains unchanged hence polyunsaturated character and low volatility problems exist. It is well known that transesterification is an effective process to overcome all these problems associated with vegetable oils. It is very clear from Tables 3 and 4 that the kinematic viscosity of vegetable oils was remarkably reduced through transesterification process. Compared to transesterification, the advantage of pyrolyzed vegetable oil called pyrodiesel is that there is no requirement for a large amount of alcohol and correspondingly no production of byproduct glycerol [112,113]. Pyrodiesel, microemulsion and renewable diesel will not be treated in this study.

4. Application of jatropha oil (JO) to CI engine

Jatropha plant bears fruits from second year of its plantation and the economic yield stabilizers from fourth or fifth year onwards. The jatropha oil and its derivatives can be used as a liquid fuel for compression ignition engine. Depending on variety, the decorticated seed of jatropha contain 43–59% of oil. In Madagascar, Cape Verde and Benin, the seed oil of jatropha was used as a diesel fuel substitute during the Second World War [114].

There are review papers on covering the biology, chemistry, toxicity of seeds and detoxification and various industrial uses including the biodiesel production from jatropha oil [72,115]. However, the application of JO to CI engines was discussed in part in those papers. The application method of jatropha oil to CI engine can be classified with neat JO, fuel modification such as blending with other fuels, mostly with diesel fuel, biodiesel, biodiesel blends and degumming [116] and engine modification such as preheating and dual fuelling.

4.1. JO

The performance of neat jatropha oil in the application to the single cylinder water-cooled direct injection diesel engine developing a power output of 3.7 kW at the rated speed of 1500 rpm at various output have been investigated as the basis for comparison with the blending, biodiesel and dual fuel operation techniques by Kumar et al. [117]. They found that jatropha oil resulted in a slightly reduced thermal efficiency as compared to diesel. HC emission was higher with jatropha oil as compared to diesel. The maximum smoke level with jatropha oil was highest among that of its ester and diesel. Ignition delay was higher with neat jatropha oil. In addition, lower heat release rate are found with jatropha oil.

The test results on a single-cylinder direct-injection engine operating on neat jatropha oil as well as blends of diesel and jatropha oil were presented by Forson et al. [83] and Agarwal and Agarwal [118]. Their tests showed that jatropha oil could be conveniently used as a diesel substitute in a diesel engine.

Reddy and Ramesh [119] reported the experimental work on a CI engine fuelled with jatropha oil. They found that when the injection timing is retarded with enhanced injection rate, a significant improvement in performance and emission was noticed. At full output, NO level and smoke with jatropha oil are 1162.5 ppm and 2 BSU, respectively, while they are 1760 ppm and 2.7 BSU with diesel. It was found that the brake thermal efficiency increases when the injection rate is lowered with jatropha oil. They concluded that a significant improvement in performance, emissions and combustion parameters can be obtained by properly optimizing the injector opening pressure, injection timing, injection rate and enhancing the swirl level when a diesel engine is to be operated with neat jatropha oil.

For agricultural applications where small amounts of fuel are consumed in every engine, use of neat vegetable oil is likely to be more attractive than the biodiesel [119]. Even though the neat jatropha oil is proper to apply for short-term use such as the agricultural machinery, pump operation, etc. it is hardly find the test results on those engines.

The application of neat vegetable oil to CI engines results in increased volumetric fuel consumption and brake specific fuel consumption. Emissions of CO and HC were found to be higher, whereas NOx and PM emissions were lower compared to mineral diesel [120]. The reason for the PM abatement effect was investigated by Klein-Douwel et al. [121] from the sooting and

chemiluminescence behavior of bio-derived fuels including neat JO and JO biodiesel. They found that JO was found to form soot on the leeward of the liquid spray, whereas for most other fuels soot was first observed further downstream. The oxygenated molecular structure is found to have an effect on soot formation, with esters being less effective in soot abatement. Therefore, they concluded that the soot abatement effect of oxygen in the bio-derived fuels might be counterbalanced by their content of double bonds, which favors soot formation.

Chauhan et al. [122] recently conducted an experimental study on the performance and emission characteristics of CI engine fuelled with neat JO. The experimental results showed that the thermal efficiency of the engine was lower, while the BSFC was higher with JO compared with diesel fuel. The level of NOx emission from JO during the entire experimental condition was lower than those of diesel fuel. However, CO, HC and CO_2 emissions from JO were higher than those of diesel fuel.

4.2. JO blends

The application of jatropha oil blended with diesel fuel [83,123,124] and methanol [117] to CI engine have been reported by many researchers in the literature.

Pramanik [123] reported the performance of the single cylinder CI engine using jatropha oil blended with diesel fuel and compared the results with the performance obtained with neat jatropha oil and diesel fuel. Among the various blends, the blends containing up to 30% (v/v) jatropha oil have viscosity values close to that of diesel fuel at the range of 35–40 °C. They found that engine performance was significantly improved compared to that of neat jatropha oil. The specific fuel consumption and the exhaust gas temperature of the blends were reduced due to decrease in viscosity of the vegetable oil. The exhaust gas temperature, which is related to the formation of NOx, of 20:80 jatropha/diesel blend shows the very close to that of diesel fuel. They concluded that up to 50% jatropha oil can be substituted for diesel use in a CI engine without any major operational difficulties.

Forson et al. [83] presented the test results of blends of jatropha oil and diesel fuel in proportions of 97.4%/2.6%, 80%/20% and 50%/50% by volume on a single-cylinder direct injection engine and compared with the test results of diesel fuel and neat jatropha oil. They found that neat jatropha oil, neat diesel and blends of jatropha oil and diesel fuel exhibited similar performance and broadly similar emission levels under comparable operating condition. They concluded that the jatropha oil can be used as an ignition-accelerator additive for pure diesel fuels when 2.6% by volume of the jatropha is introduced into pure diesel fuel.

Agarwal and Agarwal [118] had measured the viscosity of jatropha oil blended with diesel fuel with blending ratio. They found that viscosities of jatropha oil up to 30% blending with diesel fuel were found close to diesel fuel. This is identical with the result of Pramanik [123]. Brake specific fuel consumption and exhaust gas temperatures for blends of jatropha oil and diesel were found to be higher compared to diesel fuel. Thermal efficiency was also found to be close to diesel for jatropha oil blends. The emission of CO_2, CO and HC were found to be increased with increasing proportion of jatropah oil in the blends compared to diesel fuel. They concluded that performance and emission characteristics were found to be very close to diesel fuel for lower blend concentration only.

Experimental investigations have recently been carried out by Gangwar and Agarwal [124] to examine the combustion characteristics of an indirect injection (IDI) CI engine operating with jatropha oil blends with diesel (5, 10, 20 and 50% by volume). Engine tests were performed at different engine loads ranging from no load to 100% rated load at constant engine speed of 2000 rpm. Combustion starts further earlier as the proportion of jatropha oil in the blend is increased. Combustion duration is observed to be almost similar for jatropha oil blends compared to diesel fuel. However, cylinder pressure rise for all jatropha oil blends was found to be higher than diesel. They concluded that jatropha oil blends up to 50% can be used in the engine without any hardware modification in the engine without any undesirable combustion features such as knocking. In their extended study [125], they found that THC and CO emissions were lower for JO blends at lower engine loads. In addition, NOx emissions increases with increase in JO concentration in blends and smoke opacity of JO blends is higher than mineral diesel.

Most approaches for blending jatropha oil with other fuel have been tried to introduce diesel fuel as same as discussed in the above. It is, however, known that vegetable oils offer the advantages of freely mixing with alcohols and these blends can be used in the existing diesel engines without modification. Kumar et al. [117] found that blending of jatropha oil with methanol results in significant improvement in their physical properties. The viscosity and density are considerably reduced and the volatility is also improved. Results obtained from their experiments on a single cylinder diesel engine using a blend of jatropha oil and methanol showed improved brake thermal efficiency and reduced exhaust smoke emissions than neat jatropha oil. They found that NOx emission was decreased, while HC and CO emissions increased at low loads but decreased at high loads. It was also found that the amount of methanol that can be blended with jatropha oil is limited to 30% by volume due to the presence of water in alcohol and hence in turn the separation problem.

Experimental study was carried out by Agarwal and Dhar [120] for evaluating performance, combustion and emission characteristics of JO blends in DI CI engine at different load and constant engine speed. In this study, five JO blends with diesel ant neat JO biodiesel, i.e. B5, B20, B30, B50, B75 and B100 were introduced. Even though all test blends revealed similar combustion stages as mineral diesel, JO blends showed earlier start of combustion but lower heat release rate during premixed combustion phase for all engine loads. HC, CO and NO emissions were found to slightly increase with increase in JO content in the fuel blends compared to diesel.

4.3. JO biodiesel

It is widely known that biodiesel generally causes an increase in NOx emission and a decrease in unburned hydrocarbon (UHC), carbon monoxide (CO) and particulate matter (PM) emissions compared to diesel fuel [73].

A performance evaluation of JO biodiesel had been carried out by Prasad et al. [126] on a low heat rejection diesel engine and compared with the pure diesel operation of a conventional diesel engine. They found that JO biodiesel was found to be an effective substitute for use in CI engine, except for higher smoke levels.

To reduce NOx emission from CI engines running on JO biodiesel, EGR system was introduced by Suryawanshi and Deshpande [127] and Pradeep and Sharma [128]. They found that NOx emissions were decreased with the application of EGR with minor effect on fuel consumption rate, brake thermal efficiency and cylinder pressure etc. In the experimental work by Pradeep and Sharma [128], EGR level was optimized as 15% based on adequate reduction in NO emissions, minimum possible smoke, CO, HC emissions and reasonable brake thermal efficiency.

Mandepe et al. [129] introduced common rail direct injection diesel engine to determine the effects of JO biodiesel on performance and emission characteristics. They found that HC and NOx emissions are compatible to that of fossil diesel fuel. However, CO emissions tend to increase and PM emissions were significantly lower than those of diesel fuel.

The performance and emission characteristics of single cylinder direct injection CI engine operated with neat methyl esters of jatropha oil, karanja oil, and sesame oil, respectively were reported by Banapurmath et al. [130]. They found that all the methyl esters tested in this study result in a slightly reduced thermal efficiency and increased smoke, HC and CO level. It was also observed that NO emissions were lower for biodiesel operation compared to diesel. This tendency is not coincident with the general emission characteristics of biodiesel in CI engines [73].

Puhan and Nagarajan [131] presented the effect of biodiesel molecular weight, structure and number of double bond on performance and emission characteristics of diesel engine. They found that more unsaturated biodiesel fuels have higher CO, HC and smoke emissions compared to highly saturated biodiesel fuel. More NO was observed in case of highly unsaturated biodiesel fuel due to higher ignition delay and advanced fuel injection timing.

The zero-dimensional model to evaluate the performance and combustion characteristics of JO, MO and NO biodiesels was developed and the predicted results by this model were compared with the experimental results of diesel fuels [132]. They concluded that the brake thermal efficiency for vegetable oil biodiesel was nearly close to diesel fuel because the BTE was reduced 3% for JO, 4% for MO and 5% for NO, respectively. The specific fuel consumption for vegetable oil biodiesels were increased to 8%, 11% and 13% for JO, MO and NO biodiesels respectively when compared to diesel fuel.

Jindal et al. [133] investigated experimentally the effect of compression ratio and injection pressure on performance and emission characteristics in DI CI engine running on JO biodiesel. Increase in compression ratio associated with increase in injection pressure improves the performance of the engine. Increase in compression ratio leads to increase in emission of HC and exhaust temperature whereas smoke and CO emission reduces. NO emissions are found to remain unaffected at higher injection pressure. Therefore, they concluded that for fuelling the engine with JO biodiesel, one should go for higher compression ratio associated with higher injection pressure.

4.4. JO biodiesel blends

The application of JO biodiesel blended with diesel fuel [105,134–137] and palm biodiesel [138] to CI engines have been reported.

Subramanian et al. [105] tested jatropha oil biodiesel (jatropha oil methyl ester: hereafter JOME) blended with diesel in 5, 10, 15, 20 and 100% in the IDI diesel engine with EGR. Best fuel economy was observed with 10% biodiesel blended fuel in their study. In addition, NOx emissions increased while smoke emission was reduced at all speed ranges in two test modes.

The blends of 25, 50, 75 and 100% by volume of JOME and diesel were tested in single cylinder diesel engine by Sundaresan et al. [134]. They found that brake thermal efficiency of JOME blends was comparable with diesel fuel at all loads. For pollutant emissions, NOx emission from the blends of JOME was comparatively higher, smoke emission was lower and CO emission was also lower at peak load than diesel fuel.

Engine performance and exhaust emission in a single cylinder direct injection diesel engine fueled with neat JOME and its blends (B10, B20, and B50) with diesel fuel was investigated by Reksowardojo et al. [135]. The results obtained from this study in terms of engine performance and exhaust emissions are nearly similar with the other studies.

Acceptable brake thermal efficiency, brake specific energy consumption and emission characteristics in a single cylinder CI engine were obtained up to B25 of JOME and diesel fuel by Dhananjaya et al. [136]. With the increased injector opening pressure and advancing the injection timing, B20 JOME blend fuel with semi-adiabatic engine showed better combustion performance and lower exhaust emissions compared to other blends.

The blends of JOME and diesel fuel (B10 and B20) were tested in the sports utility vehicle equipped with a common rail direct injection system by Bhardwaj and Abraham [137]. It should be noted that this study is different with other investigations up to now in terms of the applicability of vegetable oils and its derivatives to the very high injection pressure system which is very sensitive to the fuel type and its quality. They concluded that the blends of JOME and diesel can replace the diesel fuel up to 10% (by volume) content for running existing common rail direct injection system without any durability problems.

It is known that stability of biodiesel is inferior compared to diesel fuel and therefore doping of biodiesel in diesel fuel will affect the stability of fuel significantly. Jatropha biodiesel has poor oxidation stability with good low temperature properties. On the other hand, palm biodiesel has good oxidative stability, but poor low temperature properties. To obtain an additive effect on these two critical properties of biodiesel by combining of jatropha and palm biodiesels, Sarin et al. [138] have examined blends of jatropha and palm biodiesel to study their physico-chemical properties. They suggested that for achieving better low temperature properties with improved oxidation stability, palm oil biodiesel blended with jatropha biodiesel at around 20–40% concentration will be an optimum mix of them. However, it is required to investigate the performance and exhaust emission characteristics of the optimum mix of jatropha–palm biodiesel when it is applied to CI engines.

Manieniyan and Sivaprakasan [139] performed the experimental investigation for performance, combustion and emission characteristics of single cylinder DI CI engine fuelled with various jatropha biodiesel blends (B20, B40, B60, and B80). They found that brake thermal efficiency decreases with increase in percentage of JO biodiesel blends. However, the brake thermal efficiency of B20 (32.22%) was nearly similar to that of diesel (32.71%), However, the effect of injection timing and injection pressure on performance, combustion and emission characteristics was not clearly explained.

Sahoo and Das [140] had analyzed the combustion characteristics such as peak cylinder pressure, time of occurance of peak pressure, heat release rate and ignition delay of biodiesel from JO, KO and Polanga oil (PO) and their blends with diesel. They recommended that PO biodiesel as the optimum fuel blend as far as the peak cylinder pressure. Ignition delays were shortened for three biodiesel blends when compared with diesel.

Sahoo et al. [141] reported the comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel blends as fuel in CI engine. Ten fuel blends (diesel, B20, B50 and B100) were tested for their use as substitute fuel for a water-cooled three cylinder tractor engine. The maximum increase in power was observed for 50% JO biodiesel at 2000 and 2100 rpm. Brake specific fuel consumption for all the biodiesel blends with diesel increased with blends and decreased with speed. There was a reduction in HC and smoke for all the biodiesel and their blends when compared with diesel. There was a slight increase in CO, NOx emissions during part throttle performance test.

Optimization of the transesterification process for biodiesel production and use of biodiesel and its blends with petrodiesel in a twin-cylinder DI CI engine were undertaken [142]. It should be noted in their results of the performance and emission tests that the NOx emission in exhaust engines for B20 blend was higher by 8%. The NOx emission of neat biodiesel (B100) was decreased by 7% compared to that of petrodiesel. The NOx emission in exhaust gases of other blends of biodiesel varied between these values.

4.5. Degummed JO

It is clear that neat vegetable oil has to be processed to take care of viscosity, cetane number and the removal of gummy materials for the utilization in diesel engine. It is well known that transesterification of neat vegetable oil is an effective way for proper use in diesel engine. Instead of it, an economical chemical process of acid treatment by which the gummy materials of vegetable oil are removed, namely, degumming is recently suggested. By degumming process, the viscosity and cetane number of vegetable oil can be improved up to certain limit so that the blends of vegetable oil with diesel can be used in diesel engine satisfactorily. The acid–caustic degumming process is schematically explained by Reksowardojo et al. [82].

A study has been conducted to investigate the performance and emission characteristics of degummed jatropha oil (DJO hereafter) and its blend with diesel (DJO10) in single cylinder DI diesel engine by Reksowardojo et al. [82]. In their study, diesel fuel, untreated jatropha oil (JO100) and its blend with diesel (JO10) were also included for the comparison purpose. Thermal efficiency of JO10 and DJO100 was found to be comparable with diesel at full loads. JO10 and DJO10 showed the slightly higher brake specific fuel consumption compared to diesel fuel. HC emissions of JO10 and DJO10 are higher than diesel fuel due to the higher viscosity of blends and in turn incomplete combustion. In addition, HC emission of JO100 and DJO100 are much higher than that of JO10 and DJO10. CO emission characteristic was very similar with HC emission trends. NOx emissions of JO10 and DJO10 were higher and comparable to diesel fuel, respectively. They pointed out that the lower cetane number causes to increase NOx emission of JO10 and DJO10. NOx emission of JO100 and DJO100 were much lower than that of diesel fuel. The cylinder pressure and rate of heat release of neat JO and DJO are lower than diesel fuel. This means that they have lower combustion temperature than diesel fuel and results in lower NOx emission. For smoke emission, JO10, DJO10, JO100 and DJO100 showed the lower value than that of diesel fuel. Even though they concluded that DJO10 is the very satisfactory blending ratio in terms of performance and exhaust emissions, the experimental results for the other blending ratios are essentially required.

A study on the comparison of performance and emission characteristics of a diesel engine fueled with three degummed non-edible vegetable oils was recently undertaken by Haldar et al. [109]. Blends of degummed oils (10, 20, 30 and 40%) such as jatropha, karanja and putranjiva oils with diesel were introduced in a single cylinder, variable CI engine at different loads and injection timings. It was observed that 20% blend of three non-edible vegetable oils with diesel give quite satisfactory performance related to brake specific fuel consumption and brake thermal efficiency. Comparing the emission characteristics such as CO, HC, NOx and particulate matter using the three non-edible vegetable oils, jatropha oil was very encouraging. They also emphasized that the degumming method offers a potentially low-cost method with simple technology for producing an alternative fuel for compression ignition engines. However, it should be pointed out that around 3% reduction of viscosity for the degummed jatropha and putranjiva oils, and around 5% reduction of viscosity for the degummed karanja oil are too small compared to 10–12 times reduction of viscosity through transesterification of inedible vegetable oils.

4.6. JO dual fuelling

To solve the problems with the use of neat vegetable oil in diesel engine such as the increased smoke emission and reduced brake thermal efficiency, Kumar et al. [143] investigated the jatropha oil as pilot fuel in a dual engine with methanol being used as the primary fuel. Tests were conducted at 1500 rpm and full load with single cylinder CI engine. The brake thermal efficiency was lower when JO is used as the pilot fuel as compared to diesel being used as the pilot fuel. The smoke level with JO was higher than that with diesel even in the dual fuel mode. HC and CO emissions are higher with JO as compared to diesel and further increased in the dual fuel mode. However, it was found that JO leads to lower NO levels as compared to diesel, even in the dual fuel mode. In addition, they discussed the experimental results on combustion characteristics such as ignition delay, cylinder peak pressure, pressure rise rate, combustion duration, and heat release rate.

In their continued research, they had introduced the hydrogen to enhance the performance characteristics of a vegetable oil fuelled CI engine [144]. By introducing small amount of hydrogen along with air, a single cylinder CI engine was operated successfully. In the case of diesel being used as the pilot fuel instead of JO, the brake thermal efficiency was always higher. HC, CO and smoke emission were also lower with diesel as compared to JO. However, NO levels were higher with diesel than JO. In addition, combustion characteristics such as cylinder peak pressure, heat release rate and maximum rate of pressure rise were also higher with diesel than JO.

The various methods of applying jatropha oil and methanol such as blending, transesterification and dual fuel operation to CI engine were investigated experimentally and compared by Kumar et al. [117]. A single cylinder CI engine at constant speed of 1500 rpm with varying power output was used.

Table 5 shows the effect of different methods of using JO on performance and exhaust emission characteristics. All data are at maximum power output 37 kW. CO emission showed the same tendency with HC emission in Table 5. NO emission shows the highest in dual fuel mode and the lowest in diesel operation. It can be summarized that dual fuel operation in diesel engines leads to reduced smoke levels with improved performance. However, dual fuel engine gives poor part load performance and HC and CO emissions are higher [119].

Use of JO biodiesel and dual fuel operation with methanol induction can give better performance and reduced smoke emissions than the blend. Dual fuel operation showed the lowest smoke and NO levels [117].

4.7. JO preheating

The effect of preheating of neat JO and a blend of equal volume of JO and the diesel fuel on diesel engine performance was investigated by Forson et al. [83]. However, the effect of preheating on the performance and exhaust emissions on a diesel engine was not precisely explained.

To evaluate the performance of CI engine with preheated jatropha oil, Agarwal and Agarwal [118] carried out the experiment on the measurement of viscosity of jatropha oil at different temperatures in the range of 40–100 °C. The application of waste heat of the exhaust gases for preheating JO is adequate to bring down the viscosity in close range to diesel fuel. BSFC and exhaust

Table 5
Effect of application methods of JO on performance and emission characteristics.

	JO	Blends	Dual fuel	JOME	Diesel
BTE (%)	27.4	28.1	28.7	29.0	30.3
EGT (°C)	428	410	412	415	402
SL (BSU)	4.4	4.1	3.4	4.0	3.8
HC (ppm)	130	110	150	110	100
NO (order)	3	4	5	2	1

BTE: brake thermal efficiency, EGT: exhaust gas temperature. SL: smoke level, BSU: Bosch smoke unit.

gas temperatures for preheated JO was found to be lower compared to neat jatropha oil. Thermal efficiency was higher for heated jatropha oil compared to neat jatropha oil. CO_2, CO, HC and smoke opacity for preheated jatropha oil were found to be close to diesel fuel. They concluded that heating the jatropha oil can be used in CI engines in rural areas for agriculture, irrigation and electricity generation.

According to the experimental results by Prasad et al. [126], smoke levels were found to be higher with preheating the inedible vegetable oils compared with diesel operation. In addition, preheating results in improved energy efficiency and higher NOx emissions with inedible vegetable oils in comparison with diesel fuel.

In the performance and emission study of preheated jatropha oil on CI engine, the optimal fuel inlet temperature was found to be 80 °C considering the BTE, BSEC and gaseous emissions [145].

5. Application of karanja oil (KO) to CI engine

It should be noted that karanja oil (botanical name: *Pongamia pinnata*), honge oil [81,146], and pongamia oil [147] are using as synonym. In this study, the term, karanja oil (KO) will be used for the vegetable oil and KO biodiesel will be used for the methyl ester produced from karanja oil through transesterification.

5.1. KO and its blends

Experiments have been carried out by Prasad et al. [148] on an engine with a conventional piston and conventional liner (CPCL), and with an insulated piston and insulated line (SPSL), employing 100% replacement of diesel fuel by neat KO at room temperature (RT) and pre-heated temperature (PT) of the oil. They found that improved performance with the combination of preheating and the insulated version of the engine. An increase in injection pressure improves BSEC marginally because of the decrease in the mean diameter of the droplet. Preheating, increase in injection pressure and the insulation of the SPSL version increased NOx emission. However, NOx levels were found to be lower with neat KO compared with diesel fuel.

A diesel engine was tested by Nazar et al. [149] with karanja oil, KO biodesel and diesel as pilot fuels while LPG was used as primary fuel. They concluded that LPG can be inducted along with air in order to reduce smoke levels and improve thermal efficiency of vegetable oil and biodiesel fuelled diesel engine.

According to the work by Haldar et al. [109], the proper percentage of blend of vegetable oil with diesel required to ensure the optimum performance and low-emission characteristics was 20% for degummed KO.

5.2. KO biodiesel and its blends

According to the combustion analysis of KO biodiesel as fuel in a single cylinder diesel engine, ignition delay for KO biodiesel and their blends showed the opposite trend with diesel [140]. The increase in viscosity for petrodiesel leads to poor atomization, slow mixing, increase in spay penetration and decrease in spray angle. These result in longer ignition delay. However, they found the shorter ignition delay in the case of biodiesel and their blends. They found the reason for this opposite trend from the work by Ryan and Bagby [150]. The chemical reactions during the injection of biodiesel at high temperature led to the break down of the high-molecular weight esters. These complex chemical resulted in the formation of gases of low-molecular weight. Rapid gasification of this lighter oil in the edge of the spray spreads out the jet, and thus volatile compounds ignited earlier and reduced the ignition delay period.

At maximum load, the brake specific fuel consumption of biodiesel was higher as compared to that of diesel. The BSFC of diesel at peak load was 0.276 kg/kWh, and that of biodiesel was 0.401 kg/kWh. It is known from the review by Lapuerta et al. [68] that the specific fuel consumption when using a biodiesel fuel is expected to increase by around 14% in relation to the consumption with diesel fuel, corresponding to the increase in heating value in mass basis. However, the break specific fuel consumption in this case is increased by 45.3%, showing the remarkable difference with the expected value. In addition, they reported that HC, CO and NO emissions are higher of methyl ester of karanja oil as compared to diesel.

Srivastava and Verma [85] tested different blends with karanja oil biodiesel in two cylinder diesel engine. They concluded that the thermal efficiency is lower with biodiesel of karanja oil as compared to diesel, whereas thermal efficiency of blending is higher than that of biodiesel. They have also reported that HC, CO and NO emissions from karanja oil methyl ester was slightly higher as compared with conventional diesel fuel. HC emission of diesel at maximum load was 85 ppm, while that of biodiesel was 120 ppm due to poor mixing with air. CO emission of diesel at maximum load was reported to be 0.18% as compared to 0.21% of biodiesel. However, emissions are lower for blends as compared to biodiesel. The emissions are 0.15%, 0.16%, 0.15% and 0.18% with blends of 5%, 10%, 15% and 20%, respectively, at maximum load. NO emission in the case of biodiesel was higher than that of blends of karanja biodiesel. It was also reported that NO emission in the case of biodiesel is approximately 12% higher than that of diesel fuel, which may be due to the higher temperature of biodiesel combustion chamber.

A comparative study of CI engine characteristics using methyl and ethyl esters of KO was reported by Baiju et al. [151]. Even though the physical and chemical properties of ethyl esters were comparable with that of methyl esters, viscosity of ethyl esters was slightly higher than that of methyl esters. Cold flow properties of ethyl esters were better than those of methyl esters. In the performance test, results show that methyl esters produced slightly higher power than ethyl esters. Exhaust emissions of both esters were almost identical. NOx emissions increased by 10–25% when fuelled with neat biodiesel and diesel–biodiesel fuel blends as compared to conventional diesel fuel at part loads. However, NOx emissions decreased at full load. Exhaust emissions such as CO, HC and smoke were reduced with the use of neat biodiesel and the blends.

According to the comparative study of combustion, performance, and emissions of JO and KO biodiesels in a direct injection CI engine by Jindal et al. [152], KO biodiesel gave better thermal efficiency and specific fuel consumption than JO biodiesel, but both biodiesels performed poorer than diesel. Emissions of HC, NOx and PM were found to be lower with both biodiesels, but CO and CO2 emissions were higher with JO biodiesel and lower with KO biodiesel when compared to diesel emission. This is different results with the consensus from the most research. It was widely known that biodiesel generally causes an increase in NOx emission and a decrease in HC, CO and PM emissions when compared to diesel fuel [64,73,153].

Raheman and Phadatare [154] tested the blends of KO biodiesel and petrodiesel from 20% to 80% by volume in a single cylinder, four-stroke direct injection diesel engine having a rated output of 7.5 kW at 3000 rpm and a compression ratio of 16:1. The maximum brake thermal efficiencies were obtained to be 26.79 and 26.19% for B20 and B40 respectively, which were higher than that of diesel (24.62%). The lower brake thermal efficiency obtained for B60–B100 could be due to a reduction in the calorific value and an increase in fuel consumption as compared to B20.

It is interesting that Raheman and Phadatare [154] obtained 75% biodiesel from karajan oil in their experiment, whereas

Srivastava and Verma [85] reported that the yield of biodiesel was 84%. It is clear that the yield of karajan oil biodiesel depends on the production method.

According to the results from the experimental work by Raheman and Phadatare [154], Kapilan et al. [155] had selected B20 blend of karajan oil methyl ester in order to study the effect of injection pressure on the performance and emission of diesel engine. They found that in the range of 16–22 MPa, the injection pressure of 20 MPa results in higher brake thermal efficiency. They concluded that this may be due to better atomization and mixing of fuel with air, which results in better combustion of fuel.

In the work by Suryawanshi and Deshpande [156], neat pongamia oil methyl ester (PME) as well as the blends of different proportion of pongamia oil methyl ester and diesel was used to run a CI engine with standard injection timing and retarded injection timing. They found that the brake thermal efficiency is similar for all blends of PME as compared to diesel at standard injection timing. However, the brake thermal efficiency is higher at part load and similar at full load for all blends of PME with retarded injection timing as compared to all blends of PME with standard injection timing.

Suryawanshi and Deshpande [147], Kumar et al. [157], and Sureshkumar et al. [86] investigated the performance and combustion characteristics of KO biodiesel and its blend with diesel from 20% to 80% by volume in a single cylinder, direct injection diesel engine and compared the results with conventional diesel fuel. Kumar et al. [157] concluded that brake thermal efficiency improved when diesel engine was fuelled with 20% and 40% KO biodiesel blends. However, Suryawanshi and Deshpande [147] reported that the use of KO biodiesel and its blends with diesel results in a similar brake thermal efficiency as compared to diesel operation. Both studies found that the addition of KO biodiesel to diesel fuel has remarkably reduced HC, CO and smoke emissions but it increases NOx emission slightly (10–20% in Kumar et al. [157]). However, Sureshkumar et al. [86] reported the notable reduction in NOx emission for all the blends as compared to diesel fuel, particularly 40% and 60% of KO biodiesel blends. Kumar et al. [157], and Sureshkumar et al. [86] concluded that the blends of KO biodiesel with diesel fuel up to 40% by volume could replace diesel fuel for running the diesel engine for getting less emissions and better performance.

Investigation was conducted to study the performance and smoke emission of different proportions of KO biodiesel blends with diesel fuel (5, 10, and 15%) in DI diesel engine under different operating conditions [158]. They conclude that KO biodiesel of 10% blend with diesel fuel is an ideal alternative fuel for diesel engine.

Malhotra et al. [159] conducted the physic-chemical analysis and emission test for B20 blends of ethyl and methyl ester of Karanja (pongamia pinnata) oil. It can be seen from their result that reduction in CO and PM were observed with both blends (CO: 20% for methyl ester, 5.6% for ethyl ester, PM:22% for methyl ester and 9% for ethyl ester). However, data for NO emission was not included in this study.

KO biodiesel–diesel blends and water-KO biodiesel emulsion as well as neat KO biodiesel were introduced for identifying the most appropriate fuel variant and operating mode for running a CI engine based on performance and emission parameters [160]. KO biodiesel exhibited similar characteristics in their engine performance with sunflower oil biodiesel and the best brake specific energy consumption occurred with 22 MPa injection pressure and for neat KO biodiesel the ideal injection timing found to be slightly retarded (1.5° crank angle) compared to diesel. However, 24.5° bTDC was found to be the most appropriate for the lower blends like B2, B5 and emulsion with 10% water proportion. 71% reduction in NOx emission was obtained at full load with 5% water-in-KO biodiesel emulsion with 10% rise in BSEC for an injection pressure of 22 MPa and a timing of 23° bTDC. For part load operation 75% reduction in NOx emission was observed for 10% water-in-KO biodiesel emulsion at an injection pressure of 22 MPa and a timing of 24.5° bTDC, accompanied by 24% increase in BSEC.

In the test of CI engine performance with blends of KO biodiesel with petrodiesel, Mahanta et al. [87] concluded that 15–20% KO biodiesel-diesel blend (B15 and B20) could be a better fuel in terms of fuel efficiency and power developed. Results obtained with B15 and B20 showed improvement in brake thermal efficiency and reduction in brake specific fuel consumption, especially at higher load. Remarkable reduction in CO and HC emission for B15 and B20 at medium and higher power output was obtained. However, the data for NOx and PM emission was not reported.

To determine the optimum fuel blend based on the BSEC, BTC and exhaust emissions, Bajpai et al. [161] introduced various diesel and KO fuel blends (5%, 10%, 15% and 20%) in a single cylinder direct injection constant speed CI engine at varying loads (0%, 20%, 40%, 60%, 80%, and 100%) Their results showed that a fuel blend of 10% KO showed higher BTE at a 60% load. The overall emission characteristics were found to be best for the case of KO10 over the entire range of engine operation.

5.3. KO dual fuelling

Experiments have been conducted on a single-cylinder direct injection CI engine operated in a single fuel mode using KO and two other VO and in dual fuel mode using producer gas with three VOs [162]. Even though dual fuel mode operation resulted in poor performance at all the loads when compared with single fuel mode at all injection timings tested, BTE was improved marginally when the injection timing was advanced. In addition, decreased smoke, NOx emission and increased CO emissions were observed for dual fuel mode for all the fuel combinations compared to single fuel operation.

Since VO produce higher smoke emissions, dual fuel operation was introduced in order to improve their emission characteristics. Therefore, comparative performance studies of CI engine operated on dual fuel mode with producer gas and KO and KO biodiesel with and without carburetor were performed by Banapurmath and Tewari [163]. In this study, a gas carburetor was suitably designed to maximize the engine performance in dual fuel model with KO–producer gas and KO biodiesel–producer gas respectively. The BTE values of 24.25%, 22.25% and 23%% were obtained with producer gas–diesel, producer gas–KO and producer gas–KO biodiesel, respectively. In addition, with dual operation emissions such as smoke and NOx were reduced considerably, but CO and HC emission increased remarkably.

6. Application of mahua oil (MO) to CI engine

In this paper, the term, mahua oil (MO) biodiesel will be used for methyl ester produced from mahua oil through transesterification. The application of mahua oil to CI engine can be grouped as neat MO and its blends and neat MO biodiesel and its blends.

6.1. MO and its blends

Agarwal et al. [106] performed the work to investigate the performance and exhaust emission of mahual oil blends in a four-stroke diesel engine and compare it with diesel fuel. It was observed by them that all mahua oil blends (10, 20 and 30%) have almost similar thermal efficiency and are very close to the thermal efficiency of diesel fuel. It should be pointed out that 30% mahua oil blend is found to be most thermally efficient from their work. It was also found that smoke density is higher for mahua oil blends

compared to diesel at lower loads. Smoke density increased with proportion of mahual oil in diesel.

There was a study on the performance and emission characteristics of CI engine fuelled with blends of diesel, MO and methanol or ethanol [111]. They concluded that macro-emulsion of MO with up to 10% alcohol can substitute diesel fuel partially with no difficulty.

6.2. MO biodiesel and its blends

Puhan et al. [164] performed a test of MO biodiesel (mahua oil methyl ester: MOME) with diesel fuel in a single cylinder direct injection CI engine and showed decrease (13%) in thermal efficiency. In the continuing work, Puhan et al. [165] tested MO biodiesel (mahua oil ethyl ester: MOEE) with diesel fuel in a same engine with the previous study and showed the comparable thermal efficiency with diesel fuel. They pointed out that this is due to the chemical composition of MOEE, which promotes the combustion process. It should be pointed out that the viscosity of MOEE (6.2 mm^2/s at 40 °C) is slightly higher than that of MOME (5.2 mm^2/s at 40 °C).

According to the works of Puhan et al. [164,165], exhaust emissions of CO, HC, NOx and smoke number were reduced around 58, 63, 12 and 70% respectively in case of MOEE and 30, 35, 4 and 11% respectively in case of MOME, compared to diesel. The amount of NOx produced for neat biodiesel of mahua oil was 50 ppm as compared to 44 ppm for diesel. This could be attributed to the increased gas temperature due to the oxygen content within biodiesel. In the continued research, MO biodiesel was tested on a single cylinder CI engine by Saravanan et al. [166]. The performance tests showed that power loss was around 13% combined with 20% increase in fuel consumption with MO biodiesel at full load. Emissions such as CO and HC were lower for MO biodiesel compared to diesel by 26% and 20% respectively. However, it should be noted that NOx emission was lesser by 4% for MO biodiesel compared to diesel.

Engine tests with MO biodiesel were conducted by Kapilan et al. [167] on a single cylinder CI engine at different injection opening pressures and loads. It was observed that the higher IOP of 20 MPa resulted in better BTE and engine efficiency of MO biodiesel is close to diesel. The engine performance with the MO biodiesel results in lower CO, HC and smoke emissions and slightly higher NO emission.

The MO biodiesel (B100), diesel fuel and their blends (B20, B40, B60, and B80) were used by Raheman and Ghadge [168] to test a single cylinder four stroke diesel engine at a compression ratio of 18:1 and injection timing of 40° before TDC with a rated output of 9 kW at 1500 rpm. In the continuing study [169], they conducted the experiment on the performance and exhaust emissions of same fuels in the same engine with the previous work, but at varying compression ratio (18:1–20:1), injection timing (35–45° bTDC). They found that biodiesel could be blended with diesel fuel up to 20% at any of the compression ratio and injection timing tested for getting nearly same performance as that with diesel.

Raheman and Ghadge [169] found that the differences of brake thermal efficiencies between diesel fuel and neat MO biodiesel were not significant at engine settings of compression ratio of 20:1 and injection timing of 40° bTDC. At full load conditions, the mean brake thermal efficiency of neat biodiesel of mahua oil was about 10.1% lower than that of diesel fuel while at lower loads, the variation was as high as 17.1% which could be attributed to the significantly lower efficiencies of neat biodiesel, especially at lower loads [168].

Godignur et al. [170] tested the performance and emission characteristics of turbocharged DI CI engine fuelled with diesel, MO biodiesel and its blends at constant speed of 1500 rpm under variable load conditions. Their results indicated that with the increase of MO biodiesel in the blends CO, HC reduced remarkably, fuel consumption and NO emission of MO biodiesel increases slightly compared with diesel. BSEC creases and thermal efficiency of engine slightly increases when operating on 20% MO biodiesel than that operating on diesel.

The improved cold flow performance of MO biodiesel by blending with ethanol and kerosene was obtained by Bhale et al. [171]. They also found that reduction of CO and NOx emissions using 20% ethanol blended fuel, but an increase in HC emission. Therefore, they concluded that ethanol blended biodiesel is totally a renewable, viable alternative fuels for improved cold flow behavior and better emission characteristics without affecting the engine performance.

Investigation of MO biodiesel as supplementary diesel fuel was carried out by Bora et al. [172]. They found that the fuel properties of MO biodiesel were within the limits specified by ASTM D 6751-2 and IS 1448 standards. The addition of MO biodiesel to diesel fuel had significantly reduced CO, HC and smoke emissions but increase in NO emission slightly. They results showed that no remarkable power reduction in the engine operation when operated with blends of MO biodiesel and diesel fuel. There are slight increase in BSFC and decrease in BTE for MO biodiesel and its blends compared to diesel fuel.

6.3. MO dual fuelling

The effect of injection timing on the performance and emissions was investigated by Kapilan and Reddy [91] in a single cylinder DI CI engine modified to work in dual fuel mode. In this study, MO biodiesel and LPG were used as pilot and primary fuels, respectively. They found that the injection time of 30 bTDC and the pilot fuel quantity of 0.5 kg/h results in better performance and lower PM, CO and HC emissions as compared to other injection timings and pilot fuel quantity. However, it should be noted that this combination results in higher NOx emission.

7. Application of linseed oil (LO) to CI engine

In this paper, the term, linseed oil (LSO) biodiesel will be used for methyl ester produced from linseed oil through transesterification. The application of linseed oil to CI engine can be grouped as neat LSO and its blends and neat LSO biodiesel and its blends. The application of macro-emulsion of LSO will be included in the discussion of LSO biodiesel.

7.1. LSO and its blends

The study on the performance characteristics and exhaust emissions of neat linseed oil in diesel engine could not be found in the literature.

Beg et al. [173] reported that brake thermal efficiency decreases as the proportion of diesel fuel decrease in the diesel fuel–linseed oil blends. They also reported the results of exhaust gas temperature, NOx emission level, CO emission level, smoke density in the semi-adiabatic type of engine by using diesel fuel–linseed oil blends according to the variation of piston coating thickness and compression ratio. Exhaust gas temperature, CO emission and smoke density are increased but NOx level is decreased in diesel fuel–linseed oil blends and biodiesel compared to diesel fuel operation.

Agawal et al. [106] found that 50% LSO blend showed maximum thermal efficiency and lowest brake specific energy consumption (BSEC), but higher smoke density, compared to all other LSO blends (10, 20, 30%, v/v).

In the theoretical study for the comparison of three vegetable oils for diesel alternative, linseed oil has the highest NOx emission

while cotton seed oil and peanut oil have lower NOx emission than diesel fuel [174]. They pointed out that combustion of vegetable oils behaves similarly to diesel fuel with higher injection pressure of 300 MPa.

7.2. LSO biodiesel and its blends

In the test of single cylinder, DI CI engine that has a rated output of 4.4 kW at 1500 rpm, the experimental results showed that the optimum fuel injection pressure was 24 MPa with neat LSO biodiesel [175]. At this optimum pressure the thermal efficiency was similar to diesel and a reduction in CO, HC and PM with an increase in NOx was noticed compared to petrodiesel.

In their continued work [176], they found that LSO biodiesel cannot be used as a sole fuel due to higher NO formation and lower BTE than those of JO biodiesel and coconut oil biodiesel. They focused on the effect of biodiesel molecular weight, structure, and the number of double bonds on diesel engine operation characteristics. They found that a biodiesel with more unsaturated fatty acid composition has more density and iodine number but less viscosity, heating value and cetane number. In addition, a more unsaturated biodiesel emits higher HC, CO and PM compared to highly saturated biodiesel fuel. It should be pointed out that more NO was observed in the case of highly unsaturated biodiesel (coconut oil biodiesel < JO biodiesel < LSO biodiesel) due to higher ignition delay and advancement in fuel injection timing.

In the test of LSO biodiesel, Beg et al. [173] found that brake specific fuel consumption of LSO biodiesel is higher than LSO blends and diesel fuel in both compression ratios. In addition, LSO biodiesel shows slightly higher brake thermal efficiency than diesel fuel with higher coating thickness. NOx emission is relatively lower in LSO biodiesel operation than LSO blends and diesel fuel operation. NOx emission level decreases 38.96% in compression ratio of 19 and 29.41% in compression ratio of 20 for LSO biodiesel compared to diesel fuel operation. Neat diesel fuel has the lowest smoke density than LSO blends and LSO biodiesel.

Agarwal et al. [106] reported that 20% LSO biodiesel blend showed maximum thermal efficiency, maximum BSEC, and lowest smoke density compared to all other LSO biodiesel blends (10, 30, 50 and 100%, v/v). An important observation is that all LSO biodiesel blends have higher thermal efficiency than diesel fuel.

The effect of injection pressure and injection timing on the performance and exhaust emission characteristics of a direct injection diesel engine operating diesel–biodiesel blends was investigated by Bhusnoor et al. [177]. They recommended that engine operation with LSO biodiesel blends at advanced injection timing was better than operation at increased injection pressure in terms of engine performance and exhaust emissions.

Use of macro-emulsion of linseed oil in CI engine was carried out by Kumar and Khare [111]. They found that the macro-emulsion of linseed oil with concentration up to 10% of alcohol gave satisfactory performance and engine ran smoothly without noise. The highest thermal efficiency higher than that of neat diesel could be obtained the operation with 60% of diesel, 30% of linseed oil and 10% of methanol.

It is required to conduct the research about the exhaust emission characteristics of LSO biodiesel blends in diesel engine. In the test of single cylinder, DI CI engine that has a rated output of 4.4 kW at 1500 rpm, the experimental results showed that the optimum fuel injection pressure was 24 MPa with LO biodiesel [175]. At this optimum pressure, the thermal efficiency was similar to diesel and a reduction in CO, HC and PM with an increase in NOx was noticed compared to diesel. The combustion analysis showed that the ignition delay was lower at higher injection pressures compared to diesel.

In their continued work [176], they found that LO biodiesel cannot be used as a sole fuel due to higher NO formation.

8. Application of rubber seed oil (RSO) to CI engine

In this paper, the term, rubber seed oil (RSO) biodiesel will be used for methyl ester produced from rubber seed oil through transesterification. The application of rubber seed oil to CI engine can be grouped as neat RSO and its blends and neat RSO biodiesel and its blends.

8.1. RSO and its blend

Geo et al. [178] had studied the performance and emission characteristics of a single cylinder diesel engine operated with preheated rubber seed oil by exhaust gas and rubber seed oil (RSO) without preheating and compared the results with those of diesel fuel. Their results show that the brake thermal efficiency increases from 26.56% to 27.89% when the fuel is preheated to a temperature of 155 °C. However, lower thermal efficiency is found in neat RSO and preheated RSO compared to diesel fuel (29.93%). Specific fuel consumption of neat RSO is more than that of diesel fuel. However, fuel preheating leads to the improvement in specific fuel consumption. NOx emission for neat RSO operation is 6.9 and 10.69 g/kWh with diesel at full load. However, NOx emission increased with increase in fuel inlet temperature, but the preheated RSO is still 20% lower than that of diesel operation. Smoke emission for neat RSO operation is much higher than that of diesel fuel. This may be due to larger SMD of vegetable oil which will increase the evaporation time and poor fuel air mixing rate. Fuel preheating can remarkably reduce the smoke lever. However, smoke level for preheated RSO operation was still higher than that of diesel fuel.

For the application of neat RSO in the electric power generation, dual fuel mode operation in diesel engines using RSO and coir-pith producer gas was introduced by Ramadhas et al. [179]. They found the decrease of engine performance and the increase of fuel consumption in addition to the higher CO emission under all load conditions.

The various blends of RSO and diesel were subjected to engine performance and emission tests and the results were compared with that for diesel by Ramadhas et al. [180]. In this study, the physical properties such as viscosity and specific gravity of the various blends of RSO were also evaluated and compared with that of diesel. They recommended that RSO–diesel blend fuel is more suitable for rural power generation because of higher carbon deposits inside combustion chamber and requirement of frequent cleaning of fuel filter and pump.

8.2. RSO biodiesel and its blend

Neat RSO, diesel and RSO biodiesel were used as fuels in the CI engine and the performance and emission characteristics of the engine were compared and analyzed [181]. They found that the lower blends of biodiesel increase the brake thermal efficiency and reduce the fuel consumption. The exhaust gas emissions are reduced with increase in biodiesel concentration.

The investigation to analyze the engine performance and exhaust emissions of CI engine fuelled with neat RSO, RSO biodiesel was carried out by Geo et al. [182]. The brake thermal efficiency is 26.53% with neat RSO, 27.89% with RSO biodiesel and 29.93% with diesel at full load. Smoke levels are higher with neat RSO and RSO biodiesel as compared to diesel. However, smoke emission is lower with RSO biodiesel than neat RSO due to the lower viscosity of RSO biodiesel. NOx emission for neat RSO operation is 6.9 and 9.6 g/kWh with RSO biodiesel and 10.7 g/kWh with diesel at full load.

A theoretical thermodynamic model was developed to analyze the performance characteristics of the CI engine fueled by biodiesel produced using unrefined RSO and its blends [110].

Baiju et al. [94] reported the experimental results using diesel, several blends of biodiesel with diesel and neat biodiesel. It should be noted that biodiesel was produced from the RSO in a three stage transesterification processes such as two acid catalyzed transesterification processes and one base catalyzed transesterification in sequence. The brake thermal efficiency was lowest with neat biodiesel in all loads. At higher loads, B10 and B20 were more efficient than diesel fuel. NOx emissions of biodiesel blends and neat biodiesel are higher than diesel at all loads. This is the opposite tendency with the results reported by Geo et al. [182]. Smoke emissions decreased with increase in biodiesel concentration in the biodiesel blends with diesel.

The performance, emission and combustion characteristics of a single cylinder CI engine running on RSO biodiesel, and its blends with diesel (B20, B60, B80) were evaluated and compared with diesel operation by Pradeep and Sharma [183]. BTE with RSO biodiesel was found to be inferior compared to petrodiesel at peak power. However, its blends with diesel shoed reasonable efficiencies, lower smoke and comparable CO and HC emissions. RSO biodiesel indicated higher smoke, CO, HC and lower NO emission at peak power.

Geo et al. [184] reported improvement in BTE and reduction in CO, HC and smoke emissions with RSO oil, RSO biodiesel–hydrogen dual fuel engine operation. However, they have also reported an increase in NOx emission. This is the similar results from jatropha–hydrogen dual fuel operation reported by Kumar et al. [144].

9. Application of cottonseed oil (CSO) to CI engine

In this paper, the term, cottonseed oil (CSO) biodiesel will be used for methyl ester produced from cotton seed oil through transesterification. The application of cottonseed oil to CI engine can be grouped as neat CSO and its blends and neat CSO biodiesel and its blends.

9.1. CSO and its blends

For the application of neat CSO directly in diesel engine, the effect of supercharging is investigated on the performance of direct injection CI engine with the use of neat CSO under varying injection pressures. It was concluded in this paper that CSO can best be utilized if supercharging is employed at the recommended injection pressure of the engine [185]. The computational examination of the combustion process of both neat CSO and diesel fuel in a heavy duty direct injection diesel engine was reported by Ruan et al. [174]. They found that neat CSO have lower NOx emissions and longer ignition delay than diesel fuel.

The studies related to neat CSO and diesel fuel blends were conducted by two research groups. He and Bao [186] concluded in their paper that 30% CSO and 70% diesel blends was practically optimal in ensuring relatively high thermal efficiency of engine, as well as homogeneity and stability of the blends. According to the works by Fontaras et al. [187,188], cotton seed oil blends with diesel at low concentration (not more than 20%, v/v) presented good fuel characteristics that comply with EN 590 standards. After applying the CSO blends successfully on Euro 2 compliant diesel vehicle for a mileage of about 21,000 km, Fontaras et al. [187] concluded that CSO blends with diesel fuel at concentrations up to 20% has no negative side effects on the vehicle operation and complies with all legislated provisions regarding fuel quality and pollutant emissions. In their continuing works [188,189], a common rail Euro 3 compliant diesel engine was tested with CSO blends. They concluded that 10% CSO and 90% diesel blends can be applied in common rail diesel engine without impacts on operation and emissions even though proper idle engine management is required. However, the engine was suffered from misfuelling at low ambient temperatures [188]. In addition, NOx appear to increase slightly in some cases.

In the nine different vegetable oils and their biodiesels, neat CSO and CSO biodiesel were included for the investigation of engine performance and exhaust emissions in single cylinder, DI CI engine [190]. They concluded that vegetable oil methyl esters gave performance and emission characteristics closer to the petrodiesel. However, vegetables oils can be used as fuel in CI engines with some modifications. It should be noted that minimum CO emissions were about 2500 ppm with CSO biodiesel among nine VO and their biodiesels except petrodiesel. In addition, NO_2 emissions with neat VOs were lower than those with petrodiesel (minimum for neat CSO) and NO_2 vlaues of the biodiesels were higher than those of the neat VO. PM emissions of neat VO were higher than that of petrodiesel.

9.2. CSO biodiesel and its blends

In the study for the effect of preheated CSO biodiesel on performance and exhaust emission of CI engine, Karabektas et al. [191] reported that optimum preheating temperature of CSO biodiesel was 90 °C due to favorable effects on BTE and CO emissions. However, this biodiesel caused higher NOx emissions.

Allen and Watts [192] postulated that the variation of the engine test between biodiesel fuel types could be caused by the differences in their atomization characteristics and impurities during production process of biodiesel. They quantitatively compared the atomization characteristics of 15 types of biodiesel including cottonseed oil and diesel fuel predicted from their viscosity and surface tension. In addition, they experimentally investigate the effect of various levels of triglyceride on the viscosity and surface tension of biodiesel fuel. They found that viscosity may be a contributing factor to the difference in performance, even though the variation of surface tension has little effect on atomization characteristics. In addition, they found that SMD shows different size according to the carbon numbers and low levels of glyceride impurities in biodiesel methyl ester shows significant changes in the viscosity.

The effects of neat CSO and CSO biodiesel on a single cylinder diesel engine performance and exhaust emissions were investigated by Altm et al. [190]. The relations between three fuels such as diesel, neat CSO and CSO biodiesel on the specific fuel consumption, NOx and smoke emissions show the similar tendency with those of diesel, neat RSO and RSO biodiesel.

Diesel engine tests fuelled with CSO biodiesel were carried out at full load–different speed range [193]. It was found in this study that the engine torque and power of CSO biodiesel was lower than that of diesel fuel in the range of 3–9% and specific fuel consumption was higher than that of diesel fuel by approximately 8–10%. In addition, NOx emission of CSO biodiesel was lower than that of diesel fuel. These are the consistent results with those of Altm et al. [190].

An experimental study was conducted to evaluate and compare the use of CSO and CSO biodiesel blended with diesel fuel at blend ratios of 10/90 and 20/80 respectively in a direct injection diesel engine [194]. It was observed that the soot emitted by CSO biodiesel blends is significantly lower than that by the corresponding neat diesel fuel, with the reduction being higher the higher the percentage of the CSO and CSO biodiesel in the blend. NO emission from CSO and CSO biodiesel blends are slightly lower than that from the corresponding diesel fuel case, with the reduction being higher the higher the concentration of the CSO and CSO biodiesel in the blend. The specific fuel consumption for CSO and CSO biodiesel blends was a little higher than that for the corresponding diesel fuel case.

In the test of CSO biodiesel and its blends with diesel (B10, B20, B30, B40, B50 and B100) in two different cars (1.6 ℓ, 4 cylinder IDI CI engine and 2.5 ℓ, DI CI engine equipped with turbocharger and EGR), Savvidis et al. [195] reported that NOx emission for CSO biodiesel and its blends with diesel were higher than those of petrodiesel. However, PM emissions were significantly lower foe biodiesel blends compared to those of petrodiesel.

The experimental results in single cylinder DI diesel engine reported by Nabi et al. [196] shoed that exhaust emissions including CO, PM and smoke emissions were reduced for all CSO biodiesel blends of B10, B20 and B30. However, a slight increase in NOx emission was experienced for CSO biodiesel blends. According to Nabi et al. [196], the reason for these effects was mainly due to the presence of oxygen in their molecular structure and additionally due to low aromatics in the CSO biodiesel blends.

As an effective solution for improving performance and emission characteristics of CSO biodiesel blends with petrodiesel, coating of combustion chamber parts such as surfaces of cylinder, head, piston, inlet and exhaust valves with a ceramic material was introduced in single cylinder DI CI engine [197]. According to the results in performance and emission values in ceramic coated and uncoated engine under same operating conditions, performance such as engine power and SFC, and emission values such as CO and smoke of the CSO blends with diesel (B20 and B40) were improved in the coated engine compared with the uncoated engine. However, an increase in NOx emissions was seen in cases of all test fuels because of higher temperature operation in the coated engine.

10. Application of neem oil (NO) to CI engine

In this paper, the term, neem oil (NO) biodiesel will be used for methyl ester produced from neem oil through transesterification. The application of neem oil to CI engine can be grouped as neat NO and its blends and neat NO biodiesel and its blends. Among the fatty acid profiles of seed oils of 75 plant species having 30% or more fixed oil in their seed/kernel, Azam et al. [35] recommended that neem (*azadirachta indica*) oil was one of the most suitable oil for use as biodiesel.

10.1. NO and its blends

Rao and Saravanan [198] compared the performance and emission characteristics of neat NO and NO blends (25%) with diesel with mineral no. 2 diesel fuel. They found that NO showed lower NOx emissions when compared with diesel and NO blends. NO blends with diesel showed slightly higher smoke intensities than diesel. CO and HC emissions of NO blends are lower compared to their neat NO and mineral diesel. The brake thermal efficiency of neat NO and its blends were comparable diesel fuel.

Experiments have been conducted by Banapurmath et al. [162] on a single cylinder, four stroke, direct injection CI engine operated in single fuel mode using NO including KO and rice bran oils. In dual fuel mode, combinations of producer gas and three vegetable oils were used at different injection timings and injection pressures. Duel fuel mode of operation resulted in poor performance at all the loads when compared with single fuel mode at all injection timings tested. Decreased smoke, NOx emissions and increased CO emissions were observed for dual fuel mode for all the fuel combinations compared to single fuel operation.

10.2. NO biodiesel and its blends

Nabi et al. [199] had reported the experimental result of combustion and exhaust emissions with diesel fuel and diesel–neem oil methyl ester (NOME) and castor oil methyl ester (0, 5, 10, 15, and 20%). In their investigation, diesel-NOME blends showed lower CO and smoke emissions compared with neat diesel fuel. With diesel-NOME blends, NOx was reduced at retarded injection timing but increased at advanced injection timing.

In the continued work, Nabi et al. [200] had investigated the combustion and exhaust emissions with diesel fuel and diesel-NOME blends (5, 10, and 15%). They found that exhaust emissions including smoke and CO were reduced, while NOx emission was increased with diesel-NOME blends for all the injection timing, compared with conventional diesel fuel. They argue that this result is identical with the result from diesel–edible biodiesel blends. However, it is clear that this is different with their former work [199].

Theoretical and experimental investigation to evaluate the performance and exhaust characteristics of neat biodiesel of NO including JO and KO had been reported [132]. They found that brake thermal efficiency for methyl esters of three non-edible vegetable oils is nearly close to diesel. In addition, CO, NOx, HC and smoke emission were reduced to 18%, 3%, 18% and 12% for NOME when compared to diesel fuel.

11. Discussion and summary

Vegetable oils selected in this article can be successfully applied in CI engine through fuel modifications and engine modifications. Fuel modifications include blending of vegetable oils with petrodiesel or other fuel, pyrolysis (thermal cracking), micro-emulsion, transesterification, and hydrodeoxygenation to reduce polymerization and viscosity. In this study, the studies related to blending of vegetable oils with petrodiesel and transesterification are included for discussion. Preheating/heated fuel line, dual fueling, and injection system modification, etc belong to engine modifications. The studies related to injection system modification were rare compared to those about preheating and dual fuelling.

The appropriate blend required to ensure optimum performance, low-emission and best combustion characteristics depends on the particular feedstock and the subsequent biodiesel formulation. Most of studies concluded that a 20% blend of VO and biodiesel with diesel works satisfactorily in the existing design of engine and parameters at which engines are operating. This trend can be applied to the biodiesel blends even though particular biodiesel shows 40% blend. In addition, the blends of biodiesel and diesel can replace the diesel fuel up to 10% by volume for running common rail direct injection system without any durability problems.

Considerable efforts such as blending, transesterification, and degumming have been made to produce vegetable oils derivatives that approximate the properties and performance of the petroleum based diesel fuels. It is found that there exists a big difference in the fuel properties of seven inedible vegetable oils considered in this review. It may be due to the different climate, soil and variety, etc. The fuel properties of seven methyl esters obtained from inedible vegetable oils also vary according to the feedstock and the selection of transesterification process. Even though the widely different fuel properties of biodiesel considered here are reported, most of fuel properties of several biodiesels are within the standards.

The application of jatropha oil to CI engine as alternative fuel can be classified as neat JO, fuel modification such as JO blends with diesel fuel, JO biodiesel, JO biodiesel blends with diesel, degumming JO, and engine modification such as preheating and dual fuelling. It should be noted that most of these applications are limited to the single cylinder condition. All the application methods of JO as a substitute for CI engine give the lower brake thermal efficiency and higher specific fuel consumption compared to diesel fuel operation. It can be found that JO biodiesel and its

blends with diesel fuel generally lead to an increase in NOx emission and a decrease in HC, CO, and PM emissions compared to petrodiesel. In dual fuel operation with JO in diesel engine, HC,CO and NOx emissions are higher and smoke level is lower that those of dual fuel operation with diesel.

Many studies on the application of KO, MO, LO, RSO, CSO and NO to CI engine had pointed out that most regulated emissions, such as those of HC, CO and PM are reduced through the use of biodiesel and its blends as a fuel in CI engine. However, there are two different interpretations concerning NOx emissions of biodiesel and its blends with diesel. Most researches have reported high NOx emissions. Meanwhile, a number of authors have confirmed lower NOx emissions with biodiesel use.

The systematic assessment of spray characteristics of neat inedible vegetable oils and its blends, neat biodiesel and its blends for use as diesel engine fuels is required.

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